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TOPICAL REVIEW

Towards a heuristic for assessing adaptation knowledge: impacts, implications, decisions and actions

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Abstract

Climate change poses a significant challenge to primary industries and adaptation will be required to reduce detrimental impacts and realise opportunities. Despite the breadth of information to support adaptation planning however, knowledge is fragmented, obscuring information needs, hampering strategic planning and constraining decision-making capacities. In this letter, we present and apply the Adaptation Knowledge Cycle (AKC), a heuristic for rapidly evaluating and systematising adaptation research by analytical foci: Impacts, Implications, Decisions or Actions. We demonstrate its application through an assessment of ten years' climate change adaptation research for New Zealand's primary industries. The letter draws on the results of systematic review, empirical analysis, workshops, interviews, narrative analyses and pathways planning to synthesise information and identify knowledge gaps. Results show the heuristic's simplicity is valuable for cross- and transdisciplinary communication on adaptation in New Zealand's primary industries. Results also provide insight into what we know and need to know with respect to undertaking adaptation planning. With the development of tools and processes to inform decision making under conditions of uncertainty—such as adaptation pathways—it is increasingly important to efficiently and accurately determine knowledge needs. The combination of systematic data collection techniques, and heuristics such as the AKC may provide researchers and stakeholders with an efficient, robust tool to review and synthesise existing knowledge, and identify emerging research priorities. Results can in turn support the design of targeted research and inform adaptation strategies for policy and practice.

1. Introduction

Climate change is inevitable. Changing patterns in annual and seasonal rainfall, increasing likelihood of sudden heatwaves, droughts, storms and floods are well documented; current impacts widely felt; and future projections point towards widening climate variability, extremes and slowly emerging impacts (Arnell and Lloyd-Hughes 2014, Cook *et al* 2015, Lewis and King 2017). While we are able to predict certain effects, determining future implications relies on probabilistic, largescale models of an interconnected climate-human-ecological system that provide finite insight into future possible conditions (Burke *et al* 2014, Harrison *et al* 2016). This implies a need for flexibility in human reactions to climate change (Folke 2006).

This need for flexibility is especially relevant for land-based primary economic activities such as agriculture—including high value horticulture and viticulture, livestock, arable, and pastoral farming (Pretty *et al* 2010, Bizikova *et al* 2012). Agriculture is inherently sensitive to changes in mean climatic conditions, changes in the frequency and severity of extremes, increases or decreased temperatures and changes in precipitation patterns that have the capacity to adversely affect producers through changes to productivity and yield, or quality (Howden *et al* 2007, Meinke *et al* 2009). Some adaptation therefore will be required. While there is consensus on the degree to which climate change is happening, its effects, and effective strategies to respond to it, are still being investigated.

To gain insight into the impacts of climate change for agriculture and inform adaptation planning, a considerable body of research has been developed in recent years (Crane *et al* 2017, Panda 2018, Vermeulen *et al* 2018, Wiréhn 2018). Studies range from biophysical models to predict changing outcomes for production and yield, to in-depth, bottom-up qualitative explorations of stakeholders' perceptions of climate risks, capacities for adaptation, and more recently, integrated assessments which seek to combine scenarios of future change, with stakeholders' experience and insights (Challinor *et al* 2014, Herrero *et al* 2014, Cradock-Henry 2017, Ausseil *et al* 2019). With adaptation knowledge being generated in different contexts, case studies and small comparative studies are providing valuable first steps in building a deep contextual understanding of climate change adaptation (Adler *et al* 2017). The knowledge base however, remains fragmented (Ford *et al* 2011, Ford and Berrang-Ford 2016, Pearce *et al* 2018).

Knowledge fragmentation and inherent communication barriers make it difficult to communicate insights across disciplines and working contexts, and collaborate effectively in order to promote adaptation planning and actions. This is especially true for transdisciplinary approaches—i.e. research involving academic, non-academic and community members—increasingly promoted in the adaptation literature as important. There is an urgent need therefore to overcome communication barriers (see Misra and Lotrecchiano 2018), and simplify the ways we pool, track and translate (research) insights to enhance impact and support the development of adaptation solutions.

In this letter, we propose the Adaptation Knowledge Cycle (AKC); a heuristic for evaluating large bodies of knowledge output. Heuristics are widely used in climate change research and can assist with reviewing, synthesising and tracking advances in understanding (Walker *et al* 2006, Preston *et al* 2015, Macintyre *et al* 2018). Our heuristic can be seen as the first step a decision-making process that first clarifies what we know and still need to know, then evaluating it against a pathways process, building on clearly communicated adaptation insights. It is effectively a perspective to sort and interpret existing research, to pair adaptation insights in such a way as to inform future adaptation decisions and planning. While we cannot overcome existing research limitations this way, we can demonstrate a way in which communication on adaptation can be simplified to better equip transdisciplinary collaboration on adaptation planning and action, and provide a potential tool for other interested reviewers. Our initial sorting process uses a systematic review (SR) methodology as well as interviews with primary industry stakeholders, combined with adaptation tracking and pathways planning.

SR methodologies have been promoted in the literature as a way to efficiently and effectively review and summarise the growing body of adaptation knowledge (Berrang-Ford *et al* 2015). Originating in the health sciences, SR is now increasingly being used for climate change adaptation to systematise knowledge at multiple scales—from local, regional, national—diverse jurisdictions, and contexts (Ford *et al* 2011, Flood *et al* 2018, Pearce *et al* 2018, Vermeulen *et al* 2018). While such reviews are welcome, there remain significant challenges to systematising and assessing the results of various studies and operationalising findings to enable effective adaptation.

Similarly, adaptation tracking can help establish a baseline to determine the status quo of adaptation planning and action, adaptation effectiveness, support and information needs (Ford *et al* 2013). What and how we track adaptation is further complicated by the inherent complexity of the field (e.g. Pearce 2018). Adaptation pathways planning has been developed to support decision making under conditions of complexity and uncertainty (Haasnoot *et al* 2013, Walker *et al* 2013), and can be seen as a meaningful addition to 'dig deeper' after the first process of tracking adaptation knowledge.

The letter is organised in four parts: the adaptation evolution and the need for tracking knowledge development as well as factors that are considered relevant for tracking exercises is next; we then discuss the AKC; and illustrate its application using the case of drought and primary industries in New Zealand. We close with conclusions identifying future avenues for research, application and refinement.

2. Adaptation in primary industries

Adaptation is both a process and a condition of altering system components, behaviour and planning to prepare for and reduce climate change impacts (Smit *et al* 1999, Nelson 2011). From the adaptation turn in the mid-1990s, to the present, the field has grown in size, scale and coverage to encompass nearly all aspects of human-environment relations in the context of climate change (Ford *et al* 2011, Agrawal *et al* 2013, Bierbaum *et al* 2013, Vink *et al* 2013). Adaptation research stands alongside mitigation as an essential response to climate change (Field *et al* 2014), as demonstrated in scientific literature, policy and planning, media and public awareness (Moser and Ekstrom 2010).

Agriculture was one of the first areas in which a focus on adaptation originally began (Smit *et al* 1999). Concern over the impacts of higher temperatures and declining precipitation on crop yields, for example, were at the centre of pioneering research modelling the vulnerability of agriculture to external stressors (Johnston and Chiotti 2000, Kenny *et al* 2000). These early studies—later described in terms of 'outcome vulnerability' (O'Brien *et al* 2007), 'end-point' or 'wounded soldier' approaches (Kelly and Adger 2000)—began with emissions trends, climate scenarios, and on to biophysical impact studies and the identifying adaptation options (Kelly and Adger 2000).

In a lot of agricultural research vis-à-vis climate change, there continues to be an emphasis on 'end-point' approaches (Kelly and Adger 2000), using crop simulation analyses (Howden *et al* 2007, Tao *et al* 2011). Downscaled climate models are used to derive target temperature increases to describe the impacts on production using the mechanisms through which climate shapes agricultural production patterns (Howden *et al* 2007). For instance, water stress (drought or water excess) and thermal stress (heat or cold) might have large impacts on plant production by disrupting the phenology (foliation, flowering, life cycle, etc), growth and yield (size, number and quality of fruits/grains) of plants and their spatial distribution (Ebi *et al* 2009). The effects on animal production are similarly modelled, through examination of the disruption to feedstock production; and the distribution and propagation of emerging diseases that could impact plant and animal production (Junk *et al* 2012, Escarcha *et al* 2018).

Such modelling studies do have significant value. Models can demonstrate the potential significance of adaptation in moderating the impacts of climate change in agriculture, however they often neglect the complex dynamics that shape how climate change is experienced and responded to by human systems. Models also tend to over-emphasise future conditions and neglect current stresses. There is also a tendency in such approaches to assume *a priori* that climate is the most significant stressor faced by producers, and also which climate stimuli are important (Meinke *et al* 2006, 2009, Wreford and Adger 2010, Gawith and Hodge 2018). Ignoring adaptation however can also lead to a serious overestimation of the damage of climate change (Tol *et al* 1998). Not only does this assumption lead to overestimations of damage, it also conveys the message that there are no actions available in the face of climate change and the only option is to mitigate emissions or suffer serious consequences (Wreford and Adger 2010).

While there continues to be considerable focus on impacts, the breadth and depth of adaptation research has broadened considerably in recent years. Researchers are now considering for example, more closely decision-making processes and the nature of barriers to adaptation: their source, strategies to circumvent, remove or lower them, and the ways in which they are influenced and constrained by local or far-removed circumstance and influence (Moser and Ekstrom 2010). In studies of farmers, empirical studies show contradictory results on farmers' adaptation. While some find that farmers do not adapt to climate change (Arbuckle *et al* 2015, Prokopy *et al* 2015, Burke and Emerick 2016) others find that farmers are currently adapting to climate change, while the 'policies supporting higher resilience of farming sector to climate change are either missing or in preparation' (Olesen *et al* 2011, p 108).

This behavioural dimension of adaptation is also a focus of close examination, in both comparative-empirical and experimental contexts (Grothmann and Patt 2005, Niles *et al* 2016, Buelow and Cradock-Henry 2018). Grothmann and Patt (2005) develop a framework for analysing the individual willingness to adapt, which is tested in an experiment by Buelow and Cradock-Henry (2018). Based on Arbuckle *et al*'s findings (2015), it can be assumed that most farmers do not interpret weather events as consequences of climate change, but instead interpret them as single events that they react to at that point in time, in a specific region, context and sector. The need for long-term adaptation is hence not self-evident, unless farmers experience climatic variability as a reoccurring, limiting factor to agricultural production and planning.

The growing breadth and depth of adaptation research, and the complexities associated with characterising and assessing it, leads Pahl-Wostl (2009) to conclude that 'only further development and application of shared conceptual frameworks taking into account the real complexity of governance regimes can generate the knowledge base needed to advance current understanding to a state that allows giving meaningful policy advice'. Integrated frameworks for assessing adaptation then, require a focus on dynamic interactions between the social, ecological, and economic state of systems. They need to be context aware, paying attention to multi-actor settings, networks, hierarchies and preferences in the social sphere, follow market-trends, preferences, interactions and transactions in the economic sphere and match those to feedback loops, structures and development of the environmental sphere (Berardi *et al* 2011, Sinclair *et al* 2014).

This complexity of both climate change as well as the effects of it on all systems makes adaptation tracking appealing as a way of continuously keep an eye on the developments at different scales in different, but interrelated spheres. Adaptation tracking seeks to characterise, monitor, and compare general trends in climate change adaptation over time. It is essential for evaluating current states and monitoring advances however, there have been few attempts to develop systematic tracking approaches (Pearce *et al* 2018). While it is highly important to know more about the state and development of adaptation, there are no commonly defined, easy to track adaptation metrics, leaving an abundance of insights and an overall fragmented understanding (Ford *et al* 2013, Ford and Berrang-Ford 2016, Pearce *et al* 2018). In the absence of agreement on indicators, data, methods of assessment and expertise, the opportunities to realise the benefits of comprehensive assessment, limit the success of learning and practice for both research and practice (e.g. Moser and Ekstrom 2010).

Notwithstanding, the capacity to track the status quo and progress of adaptation comes with a number of potential benefits: it might spur national, local and regional governments to action to see how their work compares to that of other jurisdictions (Ford *et al* 2013, Vogel and Henstra 2015, Ford and Berrang-Ford 2016, Pearce *et al* 2018). Furthermore, estimates of effective measures allow us to prioritise some activities over others and thus further reduce negative climate change impacts. All tracking needs to define what adaptation looks like in practice, how we define success and effectiveness and what kind of data sources we can rely on (Ford *et al* 2013).

To support this broader push for methods and frameworks to enable more effective adaptation tracking, we advance the following heuristic as one way to document in particular, progress towards understanding adaptation knowledge in a particular sector or knowledge domain. The relevance of identifying impacts, implications, decisions and actions in the context of agricultural adaptation is based on our collective experience working with primary industry stakeholders and end users, and empirical and conceptual studies of adaptation in Aotearoa New Zealand (New Zealand). It has been co-developed in a transdisciplinary context as part of the Sustainable Land Management and Climate Change (SLMACC) research programme, administered by New Zealand's Ministry for Primary Industries (MPI 2018). The SLMACC programme supports research to address the impacts of—and adaptation to—climate change, mitigation of agricultural greenhouse gases and improvements of forest sinks, under the paradigm of sustainable land management (Rys 2013).

As part of a review of the program's outcomes and impacts since its inception in 2007, we evaluated 32 SLMACC adaptation projects against six criteria (Science capacity and capability enhancement, Influence on science, Engagement and networks, Learning, awareness and knowledge exchange among end users, Usability of research for end users, Influence on stakeholders and impact for NZ) (Cradock-Henry *et al* 2018). We conducted a systematic literature review and prepared an annotated bibliography of the published peer-reviewed literature related to adaptation in NZ primary industries (Cradock-Henry *et al* 2019); performed a cost benefit analysis of adaptation research for pastoral farming; developed and applied the Impacts-Implications-Decisions-Actions heuristic, and classified SLMACC projects and the published literature using the heuristic to identify salient characteristics of each. We have also repeatedly discussed findings and methods with primary industry stakeholders and adaptation researchers solicit feedback on our analysis and its relevance. This process is iconic of the complexity of adaptation research: it makes it confusing and complicated to engage in conversations on the 'bigger picture', or the status quo of climate adaptation.

To remedy this, we propose the following AKC as a suggestion for evaluating adaptation research, and for simplifying complexity by sorting and categorising through an iterative process. We use it to identify and characterise adaptation knowledge by analytical foci: Impacts, Implications, Decisions and Actions. The AKC provides a tool for identification and review, and can assist with reviewing, synthesising, and assessing adaptation knowledge gaps rather than improvements of limitations in adaptation studies. As such, it is well suited for in-depth analyses of the field, assisting decision-makers and researchers alike in the process of wilding through the unclassified, existing consortium of output on adaptation, and pointing to existing knowledge gaps.

In the following section, we briefly introduce the AKC, before demonstrating its application to a case study example.

3. Adaptation knowledge cycle

Given the significant uncertainties associated with possible climate futures, there is a growing emphasis on the need to incorporate principles of adaptive management into planning processes to reduce risks and vulnerability. Adaptive management is understood as an operationalisation of adaptive governance that can bring about collaborative policy solutions to natural resource use in the agricultural sector (Folke *et al* 2005), integrating different types of knowledge and learning processes in the progress of management action (Lundmark and Jonsson 2014). In this, *management* means the process of participatory decision-making, a way of administering agricultural adaptation to climate change as a product of agricultural co-regulation.

A number of frameworks have been proposed to support adaptation planning, including pathways approaches (Haasnoot *et al* 2013), resilience assessment (Liu 2014), and bespoke tools and processes for different contexts or challenges, such as coastal hazards and sea-level rise (Barnett *et al* 2014, Lin *et al* 2017). Many of these frameworks employ a circular logic, proceeding stepwise through a deliberate process of determining and assessing impacts and the ways in which climate stressors will affect a system of concern (Bosomworth *et al* 2017).

The AKC (figure 1) is used to systematise the knowledge base with respect to impacts, implications, decisions and actions (I–I–D–A). The approach is based in part on previous work by members of the review team (Lawrence *et al* 2016) and has been further adapted to the context of the primary industries based on our collective experience and expertise (Cradock-Henry 2017, Buelow and Cradock-Henry 2018, Cradock-Henry *et al* 2018, 2019). The I–I–D–A classification originated as part of

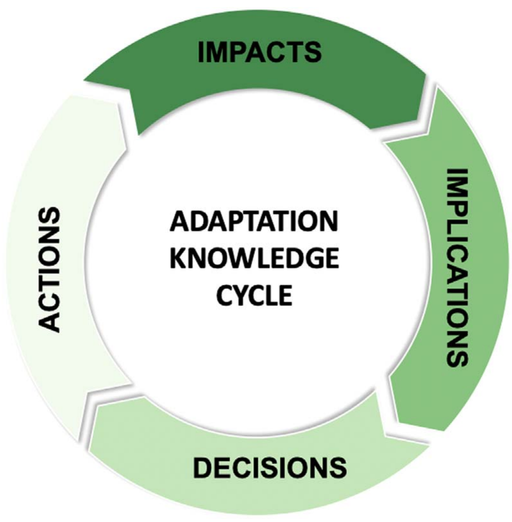

Figure 1. Adaptation knowledge cycle.

the 'Climate Change Impacts and Implications' (CCII 2015) project. The aim of the project was to determine the 'predicted climatic conditions and assessed/potential impacts and implications of climate variability and trends on New Zealand and its regional biophysical environment, the economy and society, at projected critical temporal steps up to 2100?'. In order to widen the scope beyond impacts and implications, the authors undertook research on decision-making within the CCII project to consider the ways in which stakeholders acquired and used climate information, and took action (Lawrence *et al* 2016). Subsequently, we have continued to develop and apply I–I–D–A as device for engaging with stakeholders on climate change (Lawrence *et al* 2018, Cradock-Henry *et al* 2019).

We define the four elements as follows: *Impacts*-research is focused on the direct impacts of climate change on the natural or linked natural-human environment. For primary industries, this might include research that describes changes in climatic variables that are relevant to primary industries including temperature, precipitation and any changes in climate variability or extremes. Impacts on agroecological systems, e.g. including floods and droughts, are also included (IPCC 2014). *Implications*-focused research examines the knock-on or cascading effect of specific climate impacts on the primary production system and implications for management (e.g. rising temperatures on pastures and effects on industries involved, regions, economic structures etc). Implications describe the effects for human-environment systems, such as primary industries. For example, the direct impact of higher temperatures will have implications for pasture productivity (Lee *et al* 2013), pests and invasive species (Kean *et al* 2015). Studies on *decisions* provide information to make adaptation decisions by identifying when, where and what decisions need to be made ('What can we do about the impacts or implications of climate change?'). Finally, adaptation *actions*-focused research supports changes in behaviour and implementation of on-the-ground actions for adaptation (e.g. rising temperatures on pastures in the context of different varieties introduced, different policies and their effect, sowing dates and tillage practices etc) ('How do we take action?'), and assists with monitoring the effectiveness of management interventions ('How do we know we are doing the right thing?').

This first step of categorising adaptation knowledge is combined with adaptation tracking and a pathways approach. The aim is to track and make sense of the knowledge streams that contribute to publications, findings and communication on impacts, implications, decisions or actions. Using a multi-methods approach, we analysed data sorted according to summaries we developed of relevant outputs ($n = 52$) (table 1), reviewed commentary and feedback from the researchers' responses to survey(s), and discussed outputs projects as a team. We then assessed the information provided against the Impacts–Implications–Actions–Decisions heuristic, and recorded all other key characteristics for SLMACC adaptation reports ($n = 32$).

The review of project reports was supplemented with a SR of the literature on adaptation in New Zealand's primary industries which identified relevant published literature ($n = 20$). An identical process was then applied to these outputs as well. In our empirical analysis, we have looked at *Impacts, Implications, Decisions and Actions* in the context of funding, industry sectors, research organisations involved, geographical location, uptake of research by stakeholders and their awareness of adaptation knowledge, and publications (Cradock-Henry *et al* 2019). This analyses provided an overview on the effect of research on primary sector industries and continuously fed into transdisciplinary pathways planning processes (see Cradock-Henry *et al* 2019). A detailed discussion of the review methodology is available elsewhere (Cradock-Henry *et al* 2019).

The second step was to assess adaptation knowledge against an applied adaptation pathways framework (figure 2). Adaptation pathways planning has been developed to support decision making under conditions of complexity and uncertainty (Haasnoot *et al* 2013, Walker *et al* 2013). While originally developed for flood risks, it has been widely applied in diverse settings, including for primary industries (Leith *et al* 2012, Bosomworth *et al* 2017). The pathways planning process is intended to identify a suite of adaptation options, rather than limit decision makers to a single strategy. It is open-ended, and a range of future scenarios are incorporated into the analysis to encourage an exploration of adaptation options, how they will be affected over time, and whether any options have a point at which they are no longer viable. Decision-makers determine which combination of options (or pathways) are most suitable. Once options

Table 1. Research outputs generated through systematic review and SLMACC programme

Title	Author(s)/Year	Journal/Report
Impacts of climate change on erosion and erosion control methods: a critical review	Basher *et al* (2012)	Report (SLMACC)
Climate change impacts on plant diseases affecting New Zealand horticulture	Beresford and McKay (2012)	Report (SLMACC)
Projected effects of climate change on water supply reliability in Mid-Canterbury	Bright *et al* (2008)	Report (SLMACC)
Learning from past adaptation to extreme climatic events: a case study of drought	Burton and Peoples (2008)	Report (SLMACC)
Drought, agricultural production & climate change: a way forward to a better understanding	Clark and Tait (2008)	Report (SLMACC)
Scenarios of regional drought under climate change	Clark *et al* (2011)	Report (SLMACC)
Impacts of climate change on land-based sectors and adaptation options	Clark and Nottage (2012)	Report (SLMACC)
Exploring Perceptions of Risks and Vulnerability To Climate Change in New Zealand Agriculture	Cradock-Henry (2008)	Political Science
New Zealand Kiwifruit growers' vulnerability to climate and other stressors	Cradock-Henry (2017)	Regional Environmental Change
Operationalising resilience in dairy agroecosystems	Cradock-Henry and Mortimer (2013)	Report (SLMACC)
Impacts, indicators and thresholds in sheep-and-beef land management systems	Cradock-Henry and McCusker (2015)	Report (SLMACC)
Defining climate adaptive forage traits and genetic resources	Crush (2014)	Report (SLMACC)
Tomorrow's pastures: subtropical grass growth under climate change	Dodd *et al* (2009)	Report (SLMACC)
Innovative and targeted mechanisms for supporting adaptation in the primary sector	Dunningham *et al* (2015)	Report (SLMACC)
Vulnerability of New Zealand pastoral farming to the impacts of future climate change on the soil water regime	Fowler *et al* (2008)	Report (SLMACC)
Vulnerability of pastoral farming in Hawke's Bay to future climate change: Development of a pre-screening (bottom-up) methodology	Fowler *et al* (2013)	New Zealand Geographer
The management of risk in a dryland environment	Grey *et al* (2011)	Proceedings of the New Zealand Grassland Association
Climate change risks to pastoral production systems	Guo and Trotter (2008)	Report (SLMACC)
Climate change and Aotearoa New Zealand	Hopkins *et al* (2015)	WIREs Climate Change
Impact of climate change on crop pollinator in New Zealand	Howlett *et al* (2013)	Report (SLMACC)
An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system	Kalaugher *et al* (2013)	Environmental Modelling and Software
Effects of climate change on current and potential biosecurity pests and diseases in New Zealand	Kean *et al* (2015)	Report (SLMACC)
Grassland production under global change scenarios for New Zealand pastoral agriculture	Keller *et al* (2014)	Geoscientific Model Development
Adaptation in agriculture: Lessons for Resilience from eastern regions of New Zealand	Kenny (2011)	Climatic Change
Adapting to climate change in the kiwifruit industry	Kenny and Porteous (2008)	Report (SLMACC)
Māori environmental knowledge of local weather and climate change in Aotearoa—New Zealand	King *et al* (2008)	Climatic Change
Climate-change effects and adaptation options for temperate pasture-based dairy farming systems	Lee *et al* (2013)	Journal of British Grassland Society
Improved field facilities to study climate change impacts and adaptations in pasture	Lieffering and Newton (2008)	Report (SLMACC)
Exploring climate change impacts and adaptations of extensive pastoral agricultural systems by combining biophysical simulation and farm system models	Lieffering *et al* (2016)	Agricultural Systems
Climate Smart Intensification options for New Zealand pastoral farmers: a farmer's guide to intensification options in the context of climate change	McCusker *et al* (2014)	Report (SLMACC)
Flood risk under climate change: a framework for assessing the impacts of climate change on river flow and floods, using dynamically-downscaled climate scenarios	McMillan *et al* (2010)	Report (SLMACC)
Dealing with changing risks: a New Zealand perspective on climate change adaptation	Manning *et al* (2015)	Regional Environmental Change

Table 1. (Continued.)

Title	Author(s)/Year	Journal/Report
Scenarios of storminess and regional wind extremes under climate change	Mullan *et al* (2011)	Report (SLMACC)
Empowering farmers for increased resilience in uncertain times	Nettle *et al* (2015)	Animal Production Science
Enhanced modelling capability to conduct climate change impact assessments	Newton *et al* (2008)	Report (SLMACC)
Impact of elevated atmospheric carbon dioxide concentration on pasture, production forestry and weeds	Newton *et al* (2011)	Report (SLMACC)
Detection of historical changes in pasture growth and attribution to climate change	Newton *et al* (2014)	Climate Research
How limiting factors drive agricultural adaptation to climate change	Niles *et al* (2015)	Agriculture, Ecosystems and Environment
Farmer's intended and actual adoption of climate mitigation and adaptation strategies	Niles *et al* (2016)	Climatic Change
Effects of climate change on the delivery of soil-mediated ecosystem services within the primary sector in temperate ecosystems: a review and New Zealand case study	Orwin *et al* (2015)	Global Change Biology
Farmers and Climate Change: A Cross-National Comparison of Beliefs and Risk Perceptions in High-Income Countries	Prokopy *et al* (2015)	Environmental Management
Four degrees of global warming: effects on the New Zealand primary sector	Renwick *et al* (2013)	Report (SLMACC)
Evaluating intensification trajectories in the context of climate change	Rosin *et al* (2015)	Report (SLMACC)
Changes in atmospheric circulation and temperature trends in major vineyard regions of New Zealand	Sturman and Quénol (2012)	International Journal of Climatology
Development of advanced weather and climate modelling tools to help vineyard regions adapt to climate change	Sturman *et al* (2015)	Report (SLMACC)
Designing resource-efficient ideotypes for new cropping conditions: Wheat (Triticum aestivum L.) in the High Rainfall Zone of southern Australia	Sylvester-Bradley *et al* (2012)	Field Crops Research
Improving sustainable lifetime performance of pastures: Learning from extreme climatic events	Tozer *et al* (2011)	Report (SLMACC)
Forage crop opportunities as a result of climate change	Trolove *et al* (2008)	Report (SLMACC)
Retaining Adaptive Capacity in New Zealand's ecological systems	Weller *et al* (2008)	New Zealand Journal of Agricultural Research
Framework for assessment of climate impacts on New Zealand's hydrological systems	Zemansky *et al* (2010)	Report (SLMACC)
Spatially explicit modelling of the impact of climate changes on pasture production in North Island New Zealand	Zhang *et al* (2007)	Climatic Change

are identified, they are evaluated and sequenced over time, often using a participatory process (Haasnoot *et al* 2013).

Incorporating pathways into the knowledge cycle helps to validate the focus on impacts through to actions. Both elements are conceptually and theoretically grounded in adaptive management, and emphasise planning, doing, monitoring and review (Bosomworth *et al* 2017). Second, given the growing prevalence and interest in pathways planning, it provides an efficient way to determine decision-relevant knowledge gaps, and provides a practical avenue for action. The combination complements tracking and monitoring exercises and forms the basis of an evaluation of effectiveness for improved adaptation support, information for governance as well as communication to the public (Ford *et al* 2013). Pathways planning and similar adaptation decision-support systems, provide a structured approach for decision-making when dealing with complex systems and uncertainty. Instead of reacting to systems' surprises on an ad hoc basis such processes provide a decision-oriented framework for considering a full range of adaptation pathways for a particular setting from which the most critical pathways can be determined (Haasnoot *et al* 2013, Maier *et al* 2016).

To illustrate the application of our heuristic in combination with pathways planning, the following section presents a case study example focusing on adaptation to drought for pastoral farming. We begin with a brief introduction to climate change and primary industries in New Zealand.

4. Climate change and primary industries in New Zealand

New Zealand is a small, relatively wealthy country in the Pacific. As an exporting, and trade-dependent nation, with low population density, and a history of agricultural

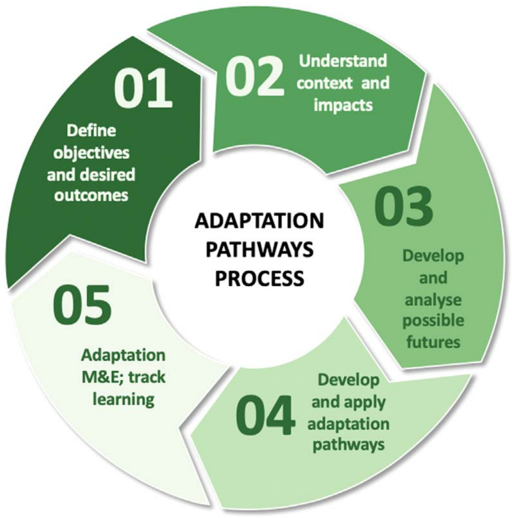

Figure 2. Adaptation pathways process (after Bosomworth *et al* 2017).

development, primary industries make a significant contribution to GDP (Statistics New Zealand 2018). Land-based primary industries in New Zealand currently operate in an environment of increasing risk and uncertainty. Primary enterprises will contend with more frequent climate crises (e.g. drought and flood), ecosystem services degradation (e.g. eroding soils, water pollution), biosecurity incursions, changing social and market demands (e.g. the demand for sustainable products) (Kenny 2011, Cradock-Henry 2017). Some of these act as persistent pressure on enterprises, while others act as short, sharp shocks. Collectively they can have a significant impact on the sector and New Zealand's economy (Stroombergen *et al* 2006, Spector *et al* 2018).

The increased frequency of such events is extremely relevant to New Zealand. Approximately half the land base is in productive pasture and arable cropping, including 1.8 million hectares of productive forest plantation. Nationally, it is a significant economic driver, employing 350 000 people, and is fundamentally important to many local and regional economies (Patterson *et al* 2006).

Climate events such as El Niño–Southern Oscillation (ENSO) have demonstrated their impacts on the economy, and there is increasing evidence of human influence on recent climate extremes affecting New Zealand (Harrington *et al* 2014). Primary sector economic activities such as pastoral farming, horticulture, viticulture and cropping are acutely vulnerable to climate change (Cradock-Henry 2017). The shift towards more intensive production and high-input systems has exposed the sector and there is further potential to create new risks and increase uncertainty for producers. Overall, as much as 79% of New Zealand's economic activity is considered vulnerable to future climate change (Fitzharris 2007, Hopkins *et al* 2015, Manning *et al* 2015).

4.1. Adaptation knowledge and drought

Drought is one of the most significant climate change related impacts for New Zealand's primary industries (Kenny 2011, Harrington *et al* 2014, Reisinger *et al* 2014). There is already evidence to suggest a close correlation between GDP and El Nino-driven drought cycles, and recent persistent dry conditions have had a marked economic impact over the last decade. Climate change is expected to increase the likelihood of dry conditions—particularly in eastern regions—which may be compounded by intensification, water restrictions, and decreased flexibility with respect to management options.

To assess the adaptation knowledge base, we identified a sub-set of reports ($n = 9$) and published peer reviewed papers ($n = 7$) from table 1, that focus explicitly on drought, or that have a significant drought-related component to the research (table 2).

To apply the AKC, and assess adaptation knowledge for drought, each research output was read multiple times by the authors. Thematic content analysis was used to code research outputs according to multiple criteria, including sector (e.g. dairy, livestock), geographic scale and focus (e.g. local, regional, national; Canterbury, Hawke's Bay); temporal scale (historical analysis; current conditions; future focused) and its contribution to adaptation knowledge (Impacts, Implications, Decisions, Actions) (table 3).

Climatic drought risk is expected to increase during this century for all areas in New Zealand that are currently drought prone (Clark *et al* 2011) and it is of significant concern for primary industries. Coding research outputs relating to drought shows a body of work on the impacts and implications of drought for primary industries, as well as some work on adaptation decision-making.

Clark and Tait (2008), for example, analysed drought risk in combination with economic analysis to consider the implications for risk management, while Burton and Peoples (2008) extended that even further to examine farmers' 'tacit' knowledge (instrumental, embedded knowledge) and the ways in which they had coped with previous droughts.

To support on-farm decision-making and enable adaptation preparedness, Cradock-Henry and Mortimer (2013) developed a model of a drought-resilient farm, incorporating psycho-social, environmental and economic indicators for monitoring and evaluation. Other practical tools are included in a review of the development and practice of climate-smart agriculture to counter the impacts of drought, high temperatures, and heavy rainfall (McCusker *et al* 2015).

There is also drought-related research in the published literature (table 3). This includes model-based studies of the impacts for wheat phenology (Sylvester-Bradley *et al* 2012) and spatial assessment of the effects of climate change on North Island pasture production (Zhang *et al* 2007). The implications for the dairy industry are considered by Lee and colleagues (Lee *et al*

Table 2. Research outputs (2007–2017) relating to drought and primary industries.

Title	Author(s)/Year	Type	Contribution to adaptation
Learning from past adaptation to extreme climatic events: a case study of drought	Burton and Peoples (2008)	Report	Examines the 'tacit' knowledge (instrumental, embedded knowledge) of farmers in NZ. It looks at past extreme weather events to see what the best coping strategies for future droughts
Drought, agricultural production and climate change: a way forward to a better understanding	Clark and Tait (2008)	Report	Recommends a programme of research that encompasses applied risk analysis with enabling science initiatives. The aim is to maintain high levels of innovation in adapting to climate change
Scenarios of regional drought under climate change	Clark *et al* (2011)	Report	Uses models (with data from the IPCC) to predict drought frequency and intensity under three major global greenhouse gas emissions scenarios (B1, A1B, and A2). Highlights the need for adaptation in regions, such as the Canterbury Plains, where there is a high likelihood that droughts will increase in frequency and intensity
Impacts of climate change on land-based sectors and adaptation options	Clark and Nottage (2012)	Report	Summarises existing data on climate change and then offers adaptation options for a range of land-based industries (dairy, sheep and beef, cropping, horticulture, forestry, viticulture)
Exploring perceptions of risks and vulnerability to climate change in New Zealand agriculture	Cradock-Henry (2008)	Journal article	Identifies vulnerabilities and adaptive capacities of agricultural producers in the Rangitaiki Plains, Bay of Plenty on the North Island, in order to contribute to the development of effective strategies to assist farmers in adapting to climate change
Impacts, indicators and thresholds in sheep-and-beef land management systems	Cradock-Henry and McCusker (2015)	Report	Uses a stability landscape model to characterise resilience in sheep-and-beef land management systems, and then develops an indicators-based evaluation framework
Operationalising resilience in dairy agroecosystems	Cradock-Henry and Mortimer (2013)	Report	Develops a novel framework for assessing resilience in dairy-agro-ecosystems
Innovative and targeted mechanisms for supporting adaptation in the primary sector	Dunningham *et al* (2015)	Report	Reviews tools and mechanisms used in New Zealand climate change adaptation communication and research, and then identifies the motivating levers of decisive action at different scales across the primary sector activities. The intention was to identify communication mechanisms to support climate change adaptation in the primary sector
The management of risk in a dryland environment	Grey *et al* (2011)	Journal article	Provides an inventory of farmers' risk management strategies, including analysis using descriptive statistics, through the issue of a questionnaire completed during face to face interviews with 24 farmers in the Hawke's Bay hill country
Climate change and Aotearoa New Zealand	Hopkins *et al* (2015)	Journal article	A desktop review examining adaptive responses to climate change in New Zealand with a focus on key industries (agriculture, tourism) and communities (coastal, Māori). The devolved structure of adaptation is also explored
Climate-change effects and adaptation options for temperate pasture-based dairy farming systems	Lee *et al* (2013)	Journal article	A desktop review that describes projected changes in climate in NZ and southeast Australia, likely effects on the feed base used in the pasture-based dairy industry and the flow-on effect on milk-solids production and profitability

Table 2. (Continued.)

Title	Author(s)/Year	Type	Contribution to adaptation
Climate Smart Intensification options for New Zealand pastoral farmers: a farmer's guide to intensification options in the context of climate change	McCusker *et al* (2014)	Report	Collates data on the threats and opportunities of farm intensification in the context of climate change
Four degrees of global warming: effects on the New Zealand primary sector	Renwick *et al* (2013)	Report	The document examines many issues under the assumption of a 4 degree rise in temperature by 2100. The issues include growing days and frosts, extreme rainfall and flooding events, pasture growth, forestry, and animal heat stress
Designing resource-efficient ideotypes for new cropping conditions	Sylvester-Bradley *et al* (2012)	Journal article	Tests modelling procedures to optimise wheat phenology according to risks of abiotic damage (frost, heat and drought) to seedling establishment and grain set. The ultimate aim of the research is to develop a Crop Design Tool that will specify resource-efficient ideotypes for any environment
Improving sustainable lifetime performance of pastures: learning from extreme climatic events	Tozer *et al* (2011)	Report (SLMACC)	Uses on-farm studies in different regions to investigate the relationships between sown functional diversity, pasture age and ingress of unsown species. Case study of Waikato one-in-one-hundred year drought (2007–2008) used to assess impact of climate extremes on between-year shifts in pasture composition
Spatially explicit modelling of the impact of climate changes on pasture production in North Island, New Zealand	Zhang *et al* (2011)	Journal article	Assessment of the potential impact of climate changes on pasture production in the North Island, New Zealand. Climate scenarios of increased temperature and increased (or decreased) rainfall were investigated by integrating a regression model for pasture production with a Geographic Information System (GIS)

2013), who examined drought in relation to feed availability and flow-on effects for productivity and profitability. There is also work from Hawke's Bay (Grey *et al* 2011) and the Bay of Plenty (Cradock-Henry 2008) on adaptation, vulnerability and risk management strategies for farming, and a national perspective on climate change risks is provided by Hopkins *et al* (2015). With respect to climate change and the primary industries, drought is the most-well-studied impact of climate change on the primary sector. There is a very little work on adaptation actions (Dunningham *et al* 2015), however there may be valuable insights that could be derived from other studies of the industry, which have looked at incentives and barriers to action, particularly for management of freshwater (Bewsell *et al* 2007, Kaine *et al* 2017).

Findings show the published literature has enhanced our understanding of drought, climate change and primary industries, particularly, through a 'whole of cycle' approach to the topic (which may have been incidental rather than deliberate). For example, the research shows an analytical focus on both impacts and implications and exploring on-farm adaptive strategies and decision-making (figure 3). With respect to planning therefore, we would suggest that there is already sufficient knowledge in the literature to inform the initial development and assessment of adaptation planning strategies, at least at a high level, and for selected industries, e.g. pastoral farming.

This is not surprising. Pasture-based farming (including dairy and livestock) have been among the largest economic drivers of New Zealand's rural economy for some time. Despite the scepticism of some in the farming community about anthropogenic climate change, the industry as a whole, likely has sufficient information to begin planning for climate change. This will still require in-depth, contextually sensitive studies to gain insight not only into regional climate variations—which are not insignificant, owing to New Zealand's island-climate and complex topography—however there is sufficient knowledge to inform development of preliminary impacts assessment, document the implications, assess the robustness of adaptation options under different scenarios of future change, and explore the barriers and enablers to adaptation action on the ground. Furthermore, by extending the scope–particularly of the 'Action' domain, there is opportunity to compare the way(s) in which other

Table 3. Coded research outputs (2007–2017) relating to drought and primary industries.

IIDA	Title	Author(s)/Year	Type	Sector	Scale/Location
Impacts	Scenarios of regional drought under climate change	Clark *et al* (2011)	Report	Multi-sector	National
	Impacts of climate change on land-based sectors and adaptation options	Clark and Nottage (2012)	Report	Multi-sector	National
	Climate change and Aotearoa New Zealand	Hopkins *et al* (2015)	Journal article	Multi-sector	National
	Four degrees of global warming: effects on the New Zealand primary sector	Renwick *et al* (2013)	Report	Multi-sector	National
	Spatially explicit modelling of the impact of climate changes on pasture production in North Island, New Zealand	Zhang *et al* (2007)	Journal article	Pastoral	National
Implications	Impacts, indicators and thresholds in sheep-and-beef land management systems	Cradock-Henry and McCusker (2015)	Report	Livestock	Regional; Hawke's Bay, Northland, Canterbury
	Climate-change effects and adaptation options for temperate pasture-based dairy farming systems	Lee *et al* (2013)	Journal article	Dairy	National
	Designing resource-efficient ideotypes for new cropping conditions	Sylvester-Bradley *et al* (2012)	Journal article	Arable	National
	Improving sustainable lifetime performance of pastures: Learning from extreme climatic events	Tozer *et al* (2011)	Report	Pastoral	National
Decisions	Learning from past adaptation to extreme climatic events: a case study of drought	Burton and Peoples (2008)	Report	Multi-sector	Regional; North Otago, South Canterbury
	Drought, agricultural production & climate change: a way forward to a better understanding	Clark and Tait (2008)	Report	Multi-sector	National
	Exploring perceptions of risks and vulnerability to climate change in New Zealand agriculture	Cradock-Henry (2008)	Journal article	Dairy	Regional; Bay of Plenty
	Operationalising resilience in dairy agroecosystems	Cradock-Henry and Mortimer (2013)	Report	Dairy	Regional; Bay of Plenty
	The management of risk in a dryland environment	Grey *et al* (2011)		Dairy	Regional; Hawke's Bay
	Climate Smart Intensification options for New Zealand pastoral farmers: a farmer's guide to intensification options in the context of climate change	McCusker *et al* (2014)	Report	Multi-sector	National
Actions	Innovative and targeted mechanisms for supporting adaptation in the primary sector	Dunningham *et al* (2015)	Report	Multi-sector	National

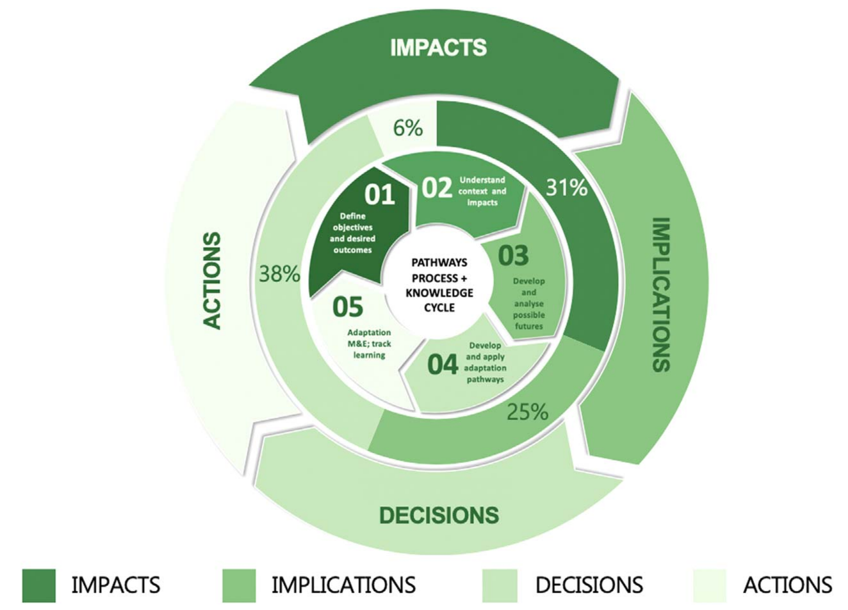

Figure 3. Drought and adaptation knowledge.

incentives have been used, for example, encouraging farmers to fence waterways to prevent stock intrusions and maintain water quality.

5. Summary and conclusions

The development and application of the AKC demonstrates the potential of the heuristic to better characterise the state of knowledge, identify research gaps, and emerging research needs and priorities. By identifying the analytical focus of research outputs and assessing each against its contribution our understanding, a more complete picture of the state of the science can be developed. Insight into direct and indirect impacts of climate change through increased or decreased precipitation, for example is necessary to fully comprehend the potential implications for land management or other agricultural activities; the decisions that stakeholders might need to make in order to adapt to aforementioned changes, and the barriers, enablers and motivations for action on the ground. The application of the heuristic also suggests that there is a need to better balance probabilistic modelling of future climate and its implications, with understanding and motivating adaptation action now. An overemphasis on knowledge production in any one part of the cycle may result in inaction—as stakeholders wait for additional information in order to make a decision. Empirical evidence shows that adaptation to current climate variability and extremes can provide the basis for adaptation to future changes, highlighting the need to explicitly consider the barriers and enablers to taking action now to reduce vulnerability.

Applying the heuristic to drought-related research in New Zealand, we showed that there is a rich and comprehensive body of knowledge for pastoral farming in particular. This research encompasses all aspects of the knowledge cycle, although more work is required for Decisions and Actions. The relative completeness of the existing knowledge base therefore suggests adaptation planning can begin immediately. Resources and efforts can be directed towards practical implementation. Rather than delaying action, existing knowledge can be used now, despite uncertainty. The need for additional information to reduce uncertainty with respect to impacts and implications, is often cited as a rationale for investment in further modelling. However, the results of the analysis suggest adaptation planning can begin immediately. Linking the review of knowledge with an adaptive management cycle, furthermore, can allow for new knowledge to be incorporated quickly and easily, refining strategies as needed.

In closing, the AKC is an initial step towards a more robust heuristic which might be used to systematically characterise the growing body of adaptation literature. The application to a case example from New Zealand does demonstrate its utility, however further conceptual, theoretical and methodological development is warranted.

Three key avenues for further refinement of the AKC and its application for assessing the knowledge base on climate change adaptation have emerged from this preliminary study. First the heuristic has only been applied to primary industries, and to a small ($n = 52$) set of research outputs (Cradock-Henry *et al* 2019). There is an opportunity therefore to apply the AKC in other contexts and consider its performance, when dealing with larger data sets or subject areas.

Second, the cycle might not only apply to other domains, but at different scales. Kolb (2014) sets out an experiential learning cycle of four stages, in which in which 'immediate or concrete experiences' provide a basis for 'observations and reflections'. These 'observations and reflections' are assimilated and distilled into 'abstract concepts' producing new implications for action which can be 'actively tested' in turn creating new experiences. Similarly, the AKC might be used as the basis for individualised evaluation of adaptation performance or knowledge needs assessment. Bespoke tools for particular industries or rural professionals could provide a means to assess their own performance, needs and actions, establish priorities and develop strategic plans.

Finally, the results can be used to articulate differences between sectors though the reasons for these differences remain underexplored. There is considerable evidence to suggest that pastoral farmers have a larger coping range than other agricultural activities. Dairy farmers are able to supplement with additional feed, reduce stock numbers or end the season early if conditions become too dry (Cradock-Henry and Mortimer 2013) and there is a well-developed literature to assist with planning. This can be contrasted with New Zealand's wine sector. Despite viticulture's economic importance and climate-sensitivity, there is very little research beyond a small number of studies on impacts, to support adaptation efforts (Cradock-Henry *et al* 2019). Furthermore, grape growers have limited short-term options at their disposal for dealing with adverse weather conditions, and long-term adaptation strategies require considerable investment and have long lead times. Further research, for example, might examine the correlation between biological limits and coping ranges, with interest in impacts or information demand to better understand adaptation options. Incorporating insights gained from pursuing these opportunities into the AKC will enhance the breadth of its applicability and its effectiveness and assist with the development of robust frameworks to track progress towards knowledge synthesis.

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Data availability statement

Any data that support the findings of this study are included within the article.

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